Structural safety of a Hubble Space Telescope Science Instrument

M. C. Lou and D. N. Brent
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, U. S. A.

ABSTRACT: This paper gives an overview of safety requirements related to structural design and verification of payloads to be launched and/or retrieved by the Space Shuttle. To demonstrate the general approach used to implement these requirements in the development of a typical Shuttle payload, the Wide Field/Planetary Camera 11, a second generation science instrument currently being developed by the Jet Propulsion Laboratory (JPL) for the Hubble Space Telescope is used as an example. In addition to verification of strength and dynamic characteristics, special emphasis is placed upon the fracture control implementation process, including parts classification and fracture control acceptability.

INTRODUCTION

For a flight hardware system to be launched and/or retrieved by the Space Shuttle, the development of its structures must address both personnel safety and safety of the mission. Safety of personnel and the Shuttle has been a paramount concern for the National Space Transportation System (NSTS) since the first Shuttle flight in 1980. This safety concern covers all aspects of the Shuttle operations, including development of Shuttle payloads. Payload structural components are classified in accordance with their likelihood of creating hazards threatening the safety of the Shuttle and its flight and ground crews. Payload developers are required to pay special attention to those components of which the failure could result in catastrophic safety hazards, Because numerous foreign and domestic agencies, private companies, and universities are developing hundreds of Shuttle payloads, the National Administration of Aeronautics and Aerospace (NASA), as the operator of the Shuttle, has established a set of uniform safety policies and requirements for payload structural development (NASA 1989). These requirements, as well as the methodologies for their implementation, were continuously revised and updated through the past decade. Safety of a Shuttle payload mission is measured by the level of reliability of the payload system. NASA does not impose agency-wide, uniform requirements for mission reliability. Mission reliability is considered a sole responsibility of the payload developer and, in general, is achieved by mission-specific structural design and verification requirements.

This paper discusses the Shuttle payload structural design and verification requirements and the general approach used to meet these requirements. Greater emphasis will be placed upon personnel safety. Also, as an example, structural development of a typical science payload, the Wide-field/Planetary, will be described to illustrate implementation of Shuttle safety requirements,

SAFETY REQUIREMENTS FOR SHUTTLE PAYLOADS

To launch and/or retrieve space flight systems (the payloads), the Space Shuttle provides many

Michael C. Lou, M/S 157-410
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109 USA

services and interfaces during the ground preparation, launch, and flight phases. In order to ensure personnel and Shuttle safety, NASA has established a uniform set of safety requirements for verifying the flight-worthiness of the payload structures (JSC 1982). These structural safety requirements can be divided into three categories: 1) strength design and verification; 2) dynamic characteristics and verification; and 3) fracture control. The requirements in each of these categories will be briefly discussed below.

Strength Design and Verification:

NASA requires that the strength of a payload structure must be demonstrated by analysis and/or testing. Strength requirements are expressed in terms of limit loads. For Shuttle safety, the limit loads are the maximum loads to be experienced by a payload while it is in the Shuttle Cargo bay. This includes all the launch, flight, and normal and emergency landing events. All payload structures are required to be designed to withstand the ultimate loads defined by multiplying the limit loads by an ultimate factor of 1.4. Compliance of this strength design requirement should be demonstrated by qualification-level static testing, Depending on whether the strength demonstraion is done on a development article or on the flight article, one of the following two options can be taken:

Option 1- Static test a developmental (i.e., the prototype) article to 1.4 times limit load.

Option 2- Static test the flight (i.e, the protoflight) article to 1.2 times limit load.

For the cases in which the adequacy of the structural design has been demonstrated by previous space applications, the protoflight static test factor of 1.2 may be reduced to 1.1.

Under some circumstances, it maybe permissible to verify the compliance of strength design by analysis alone, usually using an ultimate factor of safety higher than the required value of 1.4. Several NASA field centers have selected ultimate factors of safety between 2.0 and 3.0 for the analysis-only verification approach (JPL 1989, MSFC 1981, GSFC 1990). Due to the favorable cost and schedule considerations, as well as the desire to eliminate the risk to flight hardware and personnel imposed by static tests, This analysis-only, or commonly known as the "no-test," verification approach has become increasingly popular among the Shuttle payload developers. It should be emphasized that increasing the factor of safety for the design of a payload structure does not by itself justify the omission of static test verification. Sound engineering rationale must be developed to support the use of the no-test option for any payload development program. Some example rationale accepted by NASA/JSC include: 1) the structural design is simple with well-defined load paths, and has been thoroughly analyzed for all critical load cases; 2) the structural design has been successfully test-verified for previous Shuttle payload applications, and good correlation of test results to analytical prediction have been achieved; and 3) all safety-critical components of the payload have been identified and those that are difficult to analyze have been test verified.

Dynamic Characteristics and Verification:

The vibro-acoustic loads encountered by a payload during Shuttle launch and landing should be determined on the basis of coupled loads analysis results, The coupled load analyses are based on imposing the Shuttle launch and landing forcing functions on a synthesized mathematical model which couple the dynamic model of the payload with that of the Shuttle. The payload dynamic model used in the coupled loads analyses must capture the essential dynamic characteristics of the payload system in the frequency range up to 100 Hz. Test verification by modal survey (or equivalent tests) of the payload model is required except for payload designs whose fundamental frequency, when assuming a fixed interface with the Shuttle Cargo Bay, is higher than 35 Hz.

As for structural damping, it is required that all darnping values higher than one percent critical to be used for flight control interaction studies must be test verified.

Fracture Control Requirements.

For cyclically stressed structures containing crack-like flaws, the traditional design approach based on materials yield and ultimate strengths may not be adequate and fatigue and fracture should also be important design considerations for these structures.

Fracture mechanics analysis has been a part of the design process of aircraft structures for many decades. However, except for pressure vessels, fracture is not a major design factor for payloads launched by the expendable launch vehicles. Fracture control is the rigorous application of fracture mechanics analysis and/or testing to the prevention of crack propagation leading to catastrophic failure that may endanger the Shuttle and its flight crew. The application of fracture control to Shuttle payloads is supported by many engineering disciplines, including structural and dynamic analyses, material selection and characterization, fabrication and processes, life testing, non-destructive examination, and quality assurance.

In the early development phase of the Space Shuttle program, NASA decided that fracture control should be imposed on all payloads to assure that the presence of crack-like defects in payload components do not endanger the Shuttle and flight personnel (NASA 1989). The underlying rationale for this requirement is that no matter how carefully a payload part is made, undetected flaws can exist and, under cyclic loading, these flaws may propagate, reach unstable growth, and cause catastrophic failures. Detailed requirements for Shuttle payload fracture control are provided by NASA (NASA 1988).

Prior to a payload begin approved for integration into the Shuttle Cargo Bay, compliance of the above-listed safety requirements must be reviewed and accepted by the NASA/JSC Shuttle Payloads Safety Review Panel. JSC provides submittal requirement and safety review procedures (JSC 1989).

To improve cost effectiveness and to take advantage of recent progress of technology, NASA is constantly reviewing and updating Shuttle payload safety requirements. It is important for a Shuttle payload developer to keep current of safety requirements and to define an acceptable approach to meet the requirements at the very beginning of a payload development process. The Phase O Safety Review meeting with NASA/JSC (JSC 1989) provides the best opportunity to achieve this goal.

WF/PC INSTRUMENT

The first generation of the Wide-Field/Planetary Camera (WF/PC I) is the principal science instrument on the Hubble Space Telescope (HST) which was launched into a low Earth orbit by the Space Shuttle Discovery on April 24, 1990. The complement of HST instruments includes: two cameras (WF/PC I and Faint Object Camera), two spectrographs (Faint Object Spectrograph and High Resolution Spectrograph) and one photometer. The WF/PC I and three guidance sensors are mounted radially and the rest are axial modules in the aft of the telescope. The HST configuration is shown in Figure 1.

Due primarily to the constraints on volume, mass, and power, the WF/PC I was built as a single-string instrument with only limited redundancy and a mission life requirement of 2,5 years on-orbit. A second generation of WF/PC, the WF/PC II, was intended to serve as a replacement instrument for WF/PC 11 in case of an instrument failure and is designed for on-orbit replacement by shuttle astronauts.

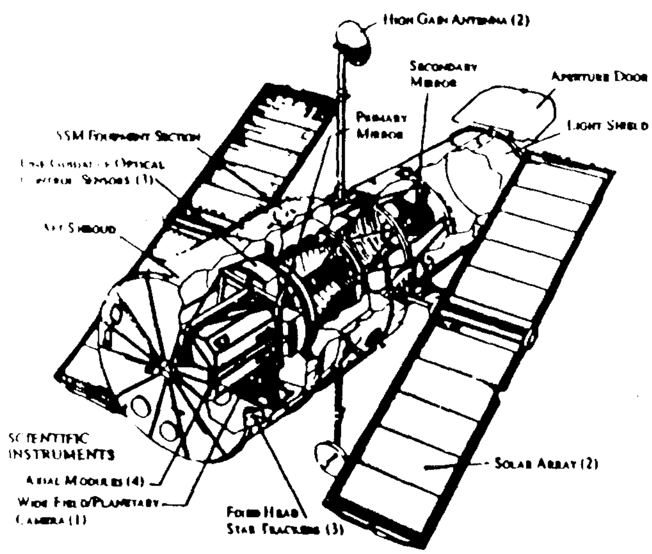

Figure 1 The Hubble Space Telescope

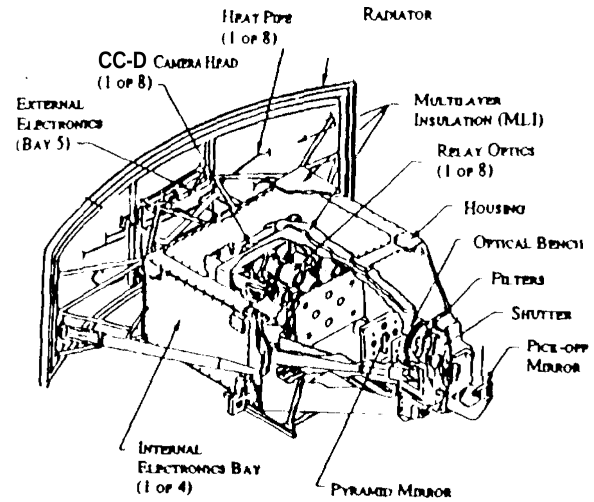

Figure 2 The WF/PC Structure

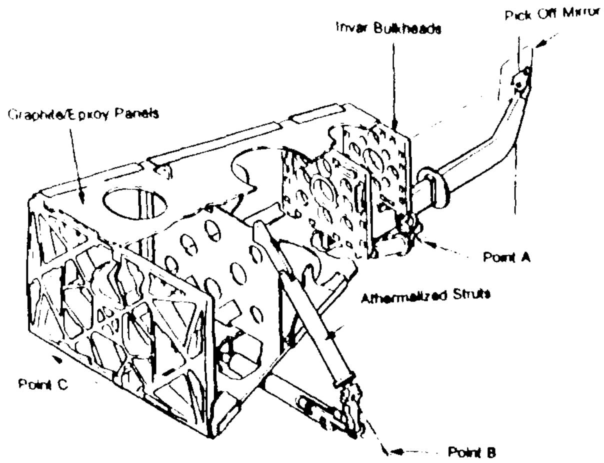

Figure 3 WF/PC Optical Bench Structure

The construction of WF/PC II was initiated prior to the launch of WF/PC 1. A few months after WF/PC I launch, it was discovered that the HST was unable to meet its intended optical performance due to spherical aberration on the primary mirror. As a consequence, most of the expected "breakthrough" science observations of very faint objects and crowded fields could not be performed. It was then decided to retro-fit the already existing design of the WF/PC II with the required optical fix to compensate for the aberrated telescope mirror. Since the structural design of WF/PC 1 and 11 are basically the same, unless it is specifically pointed out, they will be both referred to as the WF/PC in the following discussion.

The WF/PC structural system, shown in Figure 2, consists of three major elements: the optical bench, the housing, and the radiator. The optical bench supports the charge-coupled device (CCD) detectors along with an optical train that consists of critically aligned optical elements such as the pickoff mirror, a pyramid mirror, a set of fold mirrors, and Cassegrain relay optics. To compensate for the spherical aberration of the HST primary mirror, the secondary mirrors of the WF/PC 11 relay optics have been re-configured with an opposite spherical aberration. This change required extremely precise alignment of the HST primary mirror pupil image on the secondary mirror of the relay optics, To accomplish this alignment, adjustment mechanisms were added to the pickoff mirror and to three of the four fold mirrors.

The optical bench structure, shown in Figure 3, consists of four bulkheads bonded to graphite/epoxy panels. The bench is supported in a determinate manner at the three interface points via sets of athermalized struts. The fold mirrors, pyramid mirror, and relay optics are all supported on invar bulkheads. The pickoff mirror is supported at the end of a graphite/epoxy beam cantilevered off the optical bench bulkheads. The housing structure, shown in Figure 4, shields the optical bench from contamination from the outside HST Aft Shroud Environment. Aside from providing mounting surfaces for the internal electronics, the housing also supports the radiator with the use of a boron/epoxy truss structure at the end of the instrument. The housing is constructed from aluminum sheet and machined sections (6061-T6, T651).

WF/PC STRENGTH DESIGN AND VERIFICATION

Following the traditional structural development practices of JPL flight instruments, preliminary design of WF/PC structures was based on load factors given by a Mass Acceleration Curve (MAC). The MAC was developed in a semi-

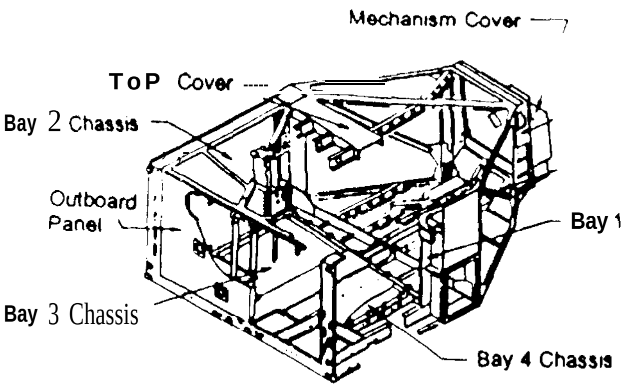

Figure 4 WF/PC Housing Structure

emprical manner (JPL 1989), and the use of which greatly simplifies preliminary sizing of flight structural members. It has been repeatedly proven by flight experience that the MAC loads are conservative and envelop the coupled loads analysis results that are used to perform final verifications of the safety margins of the structures.

For strength design and analysis of WF/PC structures, the ultimate factor of safety was selected to be 2,0 minimum. This safety factor exceeds the minimum requirements for Shuttle payloads and forms, (MSFC 1981), the basis for exempting WF/PC structures from static test qualification, The safety margins, M. S., of a WF/PC structure is defined as:

$$\text{Ms.} = \frac{\text{Materials Allowable}}{2.0 \times \text{Applied stress}} - 1.0$$

Safety margins for WF/PC structural components were determined based on results of component-level analyses, using hand stress calculations and computer modeling methods. The minimum safety margins and corresponding load conditions for the WF/PC instrument are summarized in Table 1. Under ground handling conditions where the WF/PC will be supported at Bay 5 and the housing and optical bench are supported by the radiator truss tubes, the minimum margin of safety is +0.02. Under launch loads, the minimum margin of safety for the housing structure is buckling of the top cover at +1. 11. The minimum margin of safety for the optical bench is + 0.62 for the bolts that attach the optical bench struts to the housing at the A latch.

Table1: WF/PC SAFETY MARGINS

Component	Load Condition	Safety Margin	Failure Mode
Radiator Truss Tubes	Ground Handling	+ 0.02	Compression
Top Cover	Launch	+ 1.11	Buckling
Optical Bench Bolts	Launch	+ 0.62	Tension

To verify structural adequacy and workmanship of the WF/PC, environmental tests were performed both at the sub-assembly and system level. Random vibration tests to protoflight levels were conducted on mechanisms and optical assemblies to verify their structural integrity.

Following the assembly and integration of all component parts, WF/PC system random vibration and acoustic tests to protoflight levels were conducted on the system to verify workmanship and the structural integrity of the electronics assemblies. The system random vibration tests were immediately preceded and followed by low-level sinusoidal vibration tests from 5 to 2000 Hz. These low-level sine tests were used as signature test to ensure that changes of the structural characteristics caused by the random vibration tests were noticed and identified. Figures 5 and 6 are typical responses of WF/PC structures as measured by accelerometers during vibration tests. The system level vibration tests were also followed by optical alignment tests to verify that the critical alignment of the optical elements stayed within acceptable tolerances,

WF/PC DYNAMIC CHARACTERISTICS AND VERIFICATION

The WF/PC dynamic characteristics were determined using finite element analysis. A system finite-element model (FEM) was assembled and run both to determine the instrument mode shapes and frequencies and to

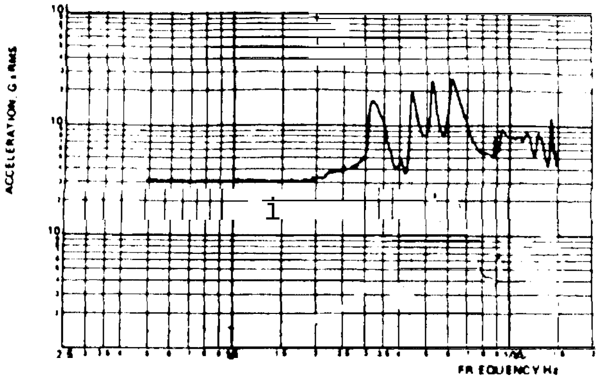

Figure 5: Typical Sine Vibration Response

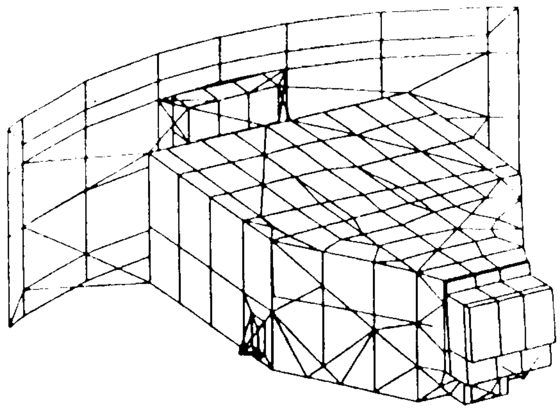

Figure 7: WF/PC FEM

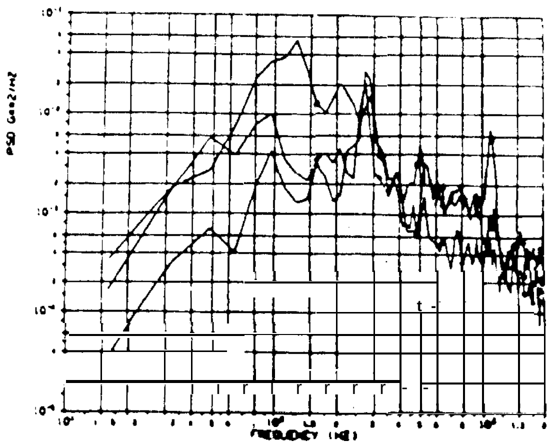

Figure 6: Random Vibration Responses

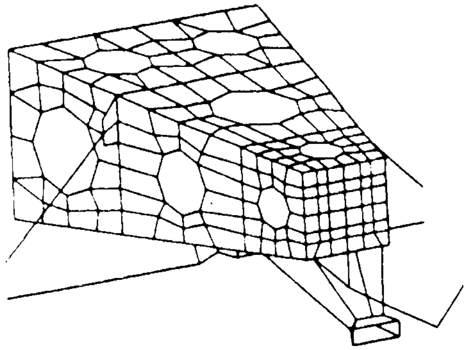

Figure 8: Optical bench FEM

be used by the launch integrator for coupled loads analyses. The usage of this FEM also included: track weight, center of gravity, and moments of inertia; determine major load paths for detailed structural analysis; and study changes in optical alignment due to the environmental effects of temperature changes, moisture resorption, and gravity release. The FEM, shown in Figure 7, is constructed from 1721 elements connecting 1145 nodes. The optical bench FEM without the housing and radiator is shown in Figure 8.

To determine dynamic characteristics of the WF/PC, modal analyses were performed. The first four modes of the WF/PC instrument are listed in Table 2. The first two modes of the instrument are bending of the housing. The third and fourth modes describe motion of the optical bench: the third mode is bending of the pickoff mirror arm; the fourth mode is a rigid translation of the optical bench through stretching of the athermalized struts. Low-level sine tests were used to verify these predicted modal frequencies,

Table 2: WF/PC Normal Modes

Mode	Frequency (Hz)	Description
1	36.9	Housing → Radiator Pitch
2	40.1	Housing → Radiator Yaw
3	41.6	POM Arm Yaw
4	51.6	Optical Bench Bounce

WF/PC FRACTURE CONTROL IMPLEMENTATION

Implementation procedures of fracture control for WF/PC are defined in the WF/PC Fracture Control Plan (JPL 1987). Following this plan, all WF/PC hardware components were reviewed and each of these components was classified into one of the following four categories:

1) *Low released mass part*: A component whose failure due to fracture will release less than 0.25 pounds (1 13.5 grams) of mass into the Shuttle Cargo bay and will not cause any catastrophic hazard to the Shuttle as a result of subsequent damage to other payloads.
2) *Contained part*: If a component is failed by a fracture, all released fragments not meeting the requirements of a low released mass part will be contained within the payload itself.
3) *Fail-safe part*: A component which can be shown by analysis or test that, after any single fracture, the remaining structure can withstand the redistributed limit loads, In addition, the failure of the part will not result in the release of any fragment that violate the requirements for a low release mass part.
4) *Fracture critical part*: Any part that can not be classified as one of the above three non-fracture-critical parts categories, Table 3 is a partial list of WF/PC fracture-critical parts.

Table 3: WF/PC Fracture-Critical Parts

Part Name	Static M.S.	# Lives	Type of NDE
Pt A strut support fittings	+4.92	Infinite	Dye Penetrant
Pts B and C support fittings	+11.?	Infinite	Dye Penetrant
Pt B Flexure Beam	+10.2	>100	Dye Penetrant
Optical Bench Strut Aluminum Tube	+14.5	14	Dye Penetrant
Pt A Strut Interface Block Fasteners	+0.62	>100	Proof Test
Purge Tube	+8.1	77	Radiographic

For each of these fracture-critical parts, non-destructive inspection was specified and conducted and a safe-life analysis performed to determine whether the part, containing a pre-existing flaw, could survive a minimum of four lifetimes. The important safe-life analyses features for a Shuttle payload, such as the WF/PC, include:

- The analysis should be based on linear elastic fracture mechanics and quantitatively predict crack growth for specific material, geometry, initial crack size and shape, environment, and loading history.
- It should be assumed that the initial crack is located at the most critical location and orientation. The size and shape of initial cracks is the largest flaw that can remain undetected following the method and level employed to detect the cracks.
- The material properties used to predict crack growth behavior shall be valid for the actual operating environment. If the initial flaw size is determined by non-destructive inspection, the average fracture toughness values should be used. If the initial flaw size is determined by proof testing, the upper bound fracture toughness values should be used.

- The loading spectrum defining a lifetime of the component should be composed of all significant load events following the non-destructive inspection or proof testing for crack detection including test, transportation, and launch.
- The effect of crack growth retardation due to intermittent overloads or crack propagation into a hole should not be included in the soft-life analysis.

All safe-life analyses of WF/PC fracture critical parts were performed employing the NASA/FLAGRO computer program and its material database (JSC 1988).

CONCLUSIONS

Structural safety requirements for Space Shuttle payloads have been discussed, with emphasis placed in three specific areas: (1) structural design and verification; (2) dynamic characterization; and (3) fracture control. An approach employed to meet the safety requirements for the successful structural development ofa typical space flight instrument, the WF/PC of HST, has been presented. Implementation details and results have also been summarized.

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